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<https://doi.org/10.1038/s43247-020-00053-y>

OPEN

Accelerating land cover change in West Africa over four decades as population pressure increased

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Rapid population growth in West Africa has exerted increasing pressures on land resources, leading to observable changes in the land cover and land use. However, spatially explicit and thematically detailed quantitative analyses of land cover change over long time periods and at regional scale have been lacking. Here we present a change intensity analysis of a Landsat-based, visually interpreted, multi-date (1975, 2000, 2013) land cover dataset of West Africa, stratified into five bioclimatic sub-regions. Change intensities accelerated over time and increased from the arid to the sub-humid sub-regions, as did population densities. The area occupied by human-dominated land cover categories more than doubled from 493,000 km² in 1975 to 1,121,000 km² in 2013. Land cover change intensities within 10 km of new settlement locations exceeded the region-wide average by up to a factor of three, substantiating the significant role of population pressure as a force of change. The spatial patterns of the human footprint in West Africa, however, suggest that not only population pressure but also changing socioeconomic conditions and policies shape the complexity of land cover outcomes.

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West Africa is a dynamic and fast developing region, which has experienced major biophysical and socio-economic changes over the past several decades¹. At the interface of the Earth surface and atmosphere, land cover has simultaneously been impacted by and contributed to those changes^{2–4}. Concerns about the pace and extent of land cover change are high on the global change research agenda, particularly with the increasing realization of the important role of land cover in the climate system^{5–7}, and of human agency as a defining force for a new human-dominated geological epoch, the Anthropocene⁸. Driven by population growth and technological development, the human impact has surpassed natural change, to the point where the vast majority of global biomes now carry the human footprint^{4,9–11}.

West Africa is no exception. The landscapes of West Africa have had a millennia-long history of human settlement, natural resource exploitation and development, and as a result they are very much anthropogenic landscapes^{12,13}, where origins of agriculture date back an estimated 4000–5000 years⁸. West Africa has experienced continued and accelerating population growth, with growth rates exceeding global averages, especially since the late 1960s (Fig. 1a). As a result, the population of West Africa has quintupled since 1950. The growing population has exerted considerable pressure on the land resources, leading to subtle modification (e.g., reduction of woody vegetation in savannas and increase of field trees¹⁴) as well as more radical conversion (e.g., transition from savanna or forest to agriculture¹⁵) of land cover. Local-scale studies from the region hint to rural population

growth as an important driver for cropland expansion in semi-arid southern Burkina Faso¹⁶ and northern Ghana¹⁷.

However, the spatial patterns, extent, and rates of such land cover changes have never been quantified and analyzed at regional scale and over long time periods, as detailed and accurate multi-date land cover data are lacking in this data-scarce region^{18–20}. On the other hand, environmental issues pertaining to land cover have been reported in the form of narratives based on anecdotal evidence and meta-analysis of case studies on deforestation, urbanization, agricultural expansion², or as part of syndromes of human–nature interactions, including the “Sahel” and the “Overexploitation” syndromes²¹. Regional-scale and long-term quantitative information on the extent and types of land cover changes will be essential in order to provide validation of and contextualization for such narratives, as well as to inform future land use planning and climate change adaptation strategies. The objectives of this research are therefore to (1) quantitatively characterize regional-scale spatiotemporal patterns of land cover over four decades and (2) infer information on the human impact on the observed land cover change by convergence of evidence from (a) relating change intensities to population densities, (b) specifically focusing on changes between natural and human-dominated land cover categories, and (c) examining change intensities at various distances from new settlements. To this end, we exploited a unique three-period (1975, 2000, 2013), thematically detailed (23 land cover categories, Fig. 1b) land cover dataset derived from expert interpretation²² of mainly multi-temporal Landsat imagery²³, designed specifically for change

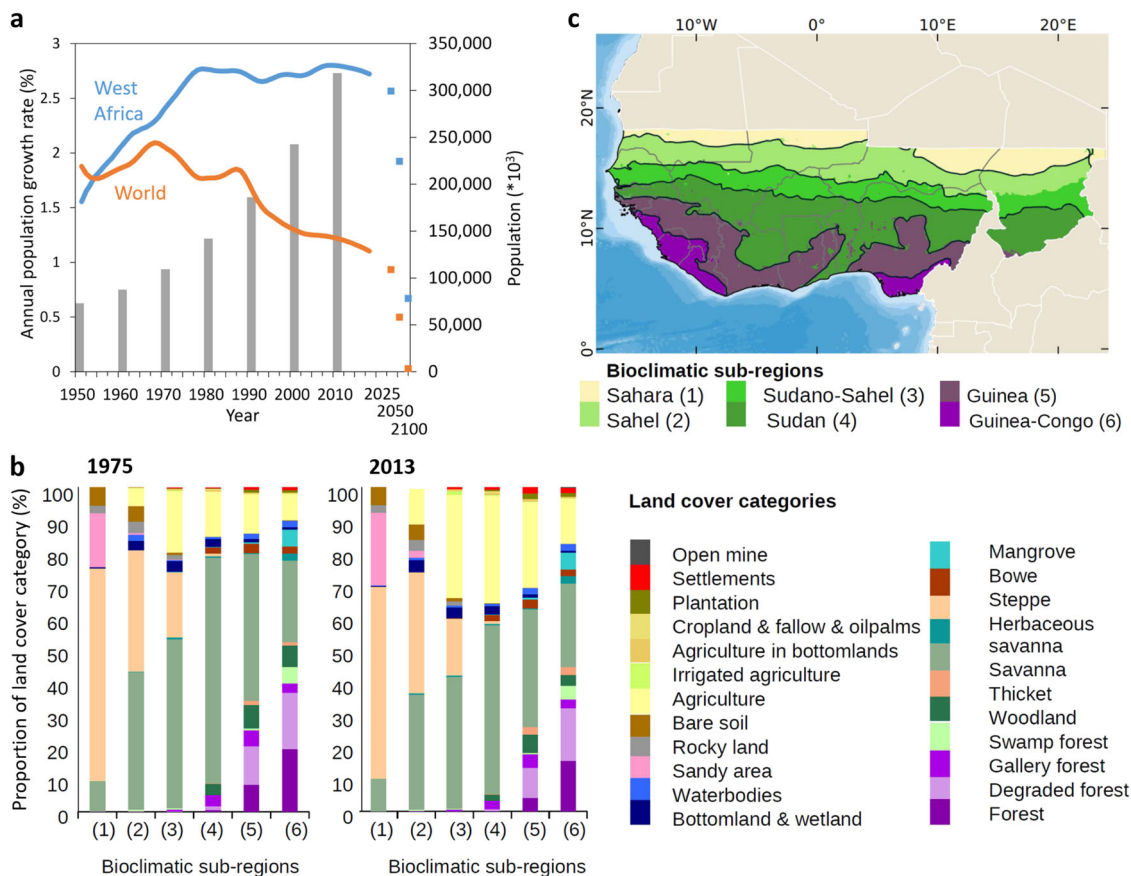


Fig. 1 Land cover and population trends in the study region. **a** Annual population growth rates in the study region (blue line) and globally (orange line) from 1950 to 2018 with projections for 2025, 2050 and 2100, as well as total population of the study region per decade (gray bars). **b** Land cover compositions of the six sub-regions in 1975 and 2013 (see Supplementary Note 1, Supplementary Table 1 and Supplementary Fig. 1 for more detail on the land cover categories). **c** Map of the study region is divided into six bioclimatic sub-regions defined by their mean annual rainfall.

analyses (Supplementary Note 1, Supplementary Table 1, Supplementary Fig. 1).

Results and discussion

The land cover change analysis followed the principles of the intensity analysis framework^{24,25} and was carried out at different levels of temporal, spatial, and thematic detail. We stratified the vast and geographically diverse study region into six sub-regions defined by their mean annual precipitation (Fig. 1c) to highlight the variety of land cover compositions and dynamics along the precipitation gradient. In addition to the differentiation into sub-regions, aggregation of land cover into only two categories, natural and human-dominated, was used to highlight the overall human footprint and its spatio-temporal expansion across the region. We note that “natural” does not imply free of human influence here, as even the natural land cover categories, such as savannas and forests, have been impacted by millennia of human presence in the majority of the study region^{8,26}. Rather, the natural land cover categories are those that were not deliberately planted or otherwise developed. Particular emphasis was placed on land cover changes associated with the expansion of settlements as a proxy for increasing population pressure (Fig. 1c). To this end, we present rates of land cover changes at increasing distances from new or expanded settlements, as well as the types of change (from-to categories) prevailing in each precipitation-defined sub-region.

Bioclimatic gradient of land cover change intensity. The land cover change intensity by time interval and sub-region represents the annualized proportion of land that experienced any change in land cover regardless of land cover categories involved. Figure 2 shows a zonal bioclimatic gradient of land cover change intensities, as well as an acceleration of change from the 1975 to 2000 time interval to the 2000–2013 time interval. Lowest land cover change intensities were observed in the most arid and least densely populated Saharan sub-region. In all but the Saharan sub-region, 2000–2013 was the more dynamic of the two time intervals, with rates of change well above the uniform change intensity of 0.66% (the hypothetical rate of change if total observed change were uniformly distributed between time intervals and among sub-regions). The greatest acceleration of land cover change between the two time intervals took place in the Guineo-Congolese sub-region, where change intensity increased by a factor of 2.7 between the two time intervals.

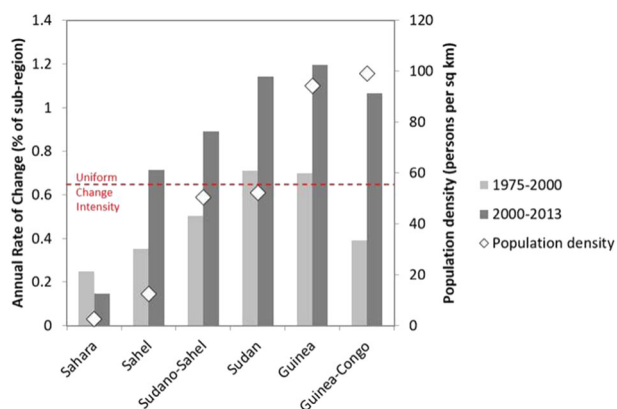


Fig. 2 Land cover change intensities. Change intensity is expressed as annualized rates of change by time interval and by sub-region. The line of the uniform rate of change represents the annual rate of change if change were evenly distributed in both time and space. Population density is the mean population density for each sub-region in 2000.

This bioclimatic gradient in change intensities is paralleled by a similar gradient in population pressures, with lowest average population densities (2.6 persons per km²) occurring in the Saharan sub-region and highest average population densities (99 persons per km²) in the Guineo-Congolese sub-region, which includes the densely populated and highly urbanized Niger delta. The association between rates of land cover change and population densities (Pearson’s $r = 0.57$, $p = 0.12$ for 1975–2000 and $r = 0.83$, $p = 0.02$ for 2000–2013) confirm population pressure as a force of change in the region²⁷, whereas the association between rates of land cover change and trends in precipitation is comparatively weak (Pearson’s $r = 0.19$, $p = 0.36$ for 1975–2000 and $r = 0.49$, $p = 0.16$).

Magnitude and intensity of change among land cover categories. Land cover categories were unevenly affected by changes, with some categories rather stable over time and others actively changing. Two metrics—the magnitude (size) and the intensity (rate) of change—were used to contrast two different aspects of land cover change. Each land cover category was analyzed as a gaining and as a losing category. In terms of the magnitude of change, agriculture was the principal gaining land cover category by a wide margin, with gains in area of 646,000 km² between 1975 and 2013 throughout the study region, followed by savanna, which gained 140,000 km². Largest area losses occurred in the natural vegetation categories, particularly in the savanna (622,000 km²), followed by losses in the forest and woodland categories (>200,000 km² combined losses) and in the steppes (113,000 km²) (Fig. 3a).

However, while the savanna category recorded the second largest gains in area (change magnitude) after agriculture, its gain intensity remains below the line of uniform change intensity. This low gain intensity, despite large area gains, identifies it as a relatively dormant gaining category, which gained at a lower rate than it would have if all gains were randomly distributed across the region²⁴. Gain intensities separated the natural land cover categories into two groups: As expected, “primary” natural land cover categories (e.g., forest, savanna, and steppes) all had low gain intensities. By contrast, “secondary” natural and cover categories, which are typically less productive and biodiverse (e.g., degraded forest, thicket, sandy surfaces) and might have resulted from a form of degradation of the “primary” natural land cover, were actively gaining, as were all of the human-dominated land cover categories. With the exception of agriculture, the human land cover categories all occupy relatively small areas to being with, thus their change magnitudes are comparatively minor. The importance of their increase is however revealed by their high change intensities of mostly >1.5% yr⁻¹ (compared to a uniform change intensity of 0.66% yr⁻¹).

On the other hand, the group of actively losing land cover categories was made up exclusively of natural land cover categories, with woodlands, degraded forests, and intact forests losing at the highest rates (1.09% yr⁻¹, 1.07% yr⁻¹, and 1.04% yr⁻¹, respectively), followed by surface water and savannas. By contrast, all human-dominated land covers emerged as dormant losing land cover categories, with losses below the line of uniform change intensity, which identifies them as unidirectionally expanding land covers²⁸.

Some land covers were highly dynamic in both directions in that they simultaneously lost and gained at high rates, changing their location but not overall size. Such swap changes alter the spatial pattern without significantly affecting the total area of a land cover category, and they go unnoticed in figures of net change²⁹. Here, categories affected by swap changes included water surfaces, wetlands, and degraded forest. The dynamics in

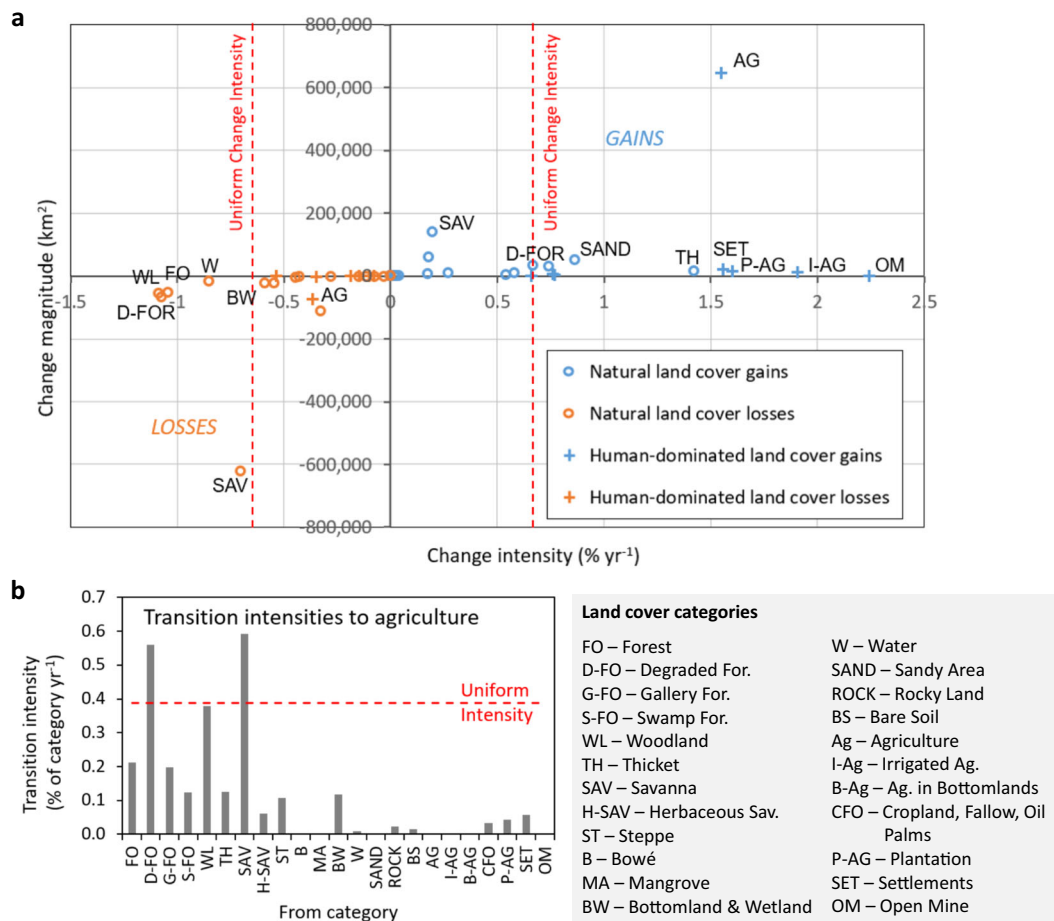


Fig. 3 Land cover change by category. **a** Magnitude (in km²) versus intensity of change (as annual rates of change % yr⁻¹) by land cover category for the entire study region from 1975 to 2013. The lines of uniform change intensity define actively changing land cover categories (beyond the lines) and dormant land cover categories (within the lines). Each land cover category appears twice, once as a gaining and once as a losing category. Only selected categories are labeled. See Supplementary Table 2 for numbers for all categories. **b** Transition intensities to agriculture from all other land cover categories from 1975 to 2013. The line of uniform transition intensity indicates what percentage of each category would transition to agriculture per year if the gains of agriculture were randomly distributed in space. It separates categories that are systematically avoided (below uniform intensity) vs. systematically targeted (above uniform intensity) for transition to agriculture. Across the region, degraded forest and savanna were systematically converted to agriculture. (See “Methods” section for details).

the first two can be attributed to seasonal and interannual variability³⁰; the case of degraded forest, which lost at a higher rate than it gained, can be explained by conversion from forest to degraded forest in some places, and from degraded forest to agriculture in others. An analysis of transition intensities to agriculture show that while degraded forest and savanna were most targeted for conversion to agriculture (as evidenced by rates of change above uniform change intensity), intact forest systematically avoided direct transition to agriculture (rate of change below uniform change intensity) (Fig. 3b).

The contrast between actively gaining human-dominated land cover categories and actively losing natural land cover categories confirms the key role of human agency on land cover change in the form of agricultural expansion, as also documented in prior, less spatially and thematically detailed remote sensing-based studies^{15,31}, statistical analyses of country level-aggregated data²⁸, and meta-analyses of case studies³². However, our results differ from the findings from other studies in some aspects: Unlike Gibbs et al. (2010)³¹, who found that the majority of agricultural expansion from 1980 to 2000 was at the expense of intact forests across the tropics, our analysis shows that across West Africa the area of degraded forests lost to agriculture amounted to more than three times the area of intact forests lost to agriculture

(35,850 vs. 10,630 km²). This relationship holds true across both time intervals and for forests in the humid tropical as well as semi-arid sub-regions. Moreover, in contrast to a remote-sensing-based study on land cover change in East Africa³³, which showed slowing down of the rate of anthropogenic impact from the decade prior to 2000 to the decade after 2000, our results for West Africa showed an acceleration of change.

Although this study was based on a dataset of great thematic detail, it still precludes insights on more subtle, within-category changes such as reduction or gain in woody cover in savannas and woodlands³⁴, changes in species composition and diversity³⁵, and shifts from low intensity to high intensity cropland with reduction in fallow^{36,37}. All of these carry the mark of anthropogenic pressure, even in the “natural” land cover categories.

Some shortcomings of the underlying data have to be acknowledged, especially in the context of analyses at the level of transitions between individual land cover categories: Although the dataset was designed explicitly to overcome the lack of accuracy associated with automated and semi-automated image classification approaches²², it bears the potential of interpretation errors and subjective bias. While some land cover types are much more reliably discerned by a qualified interpreter than by a

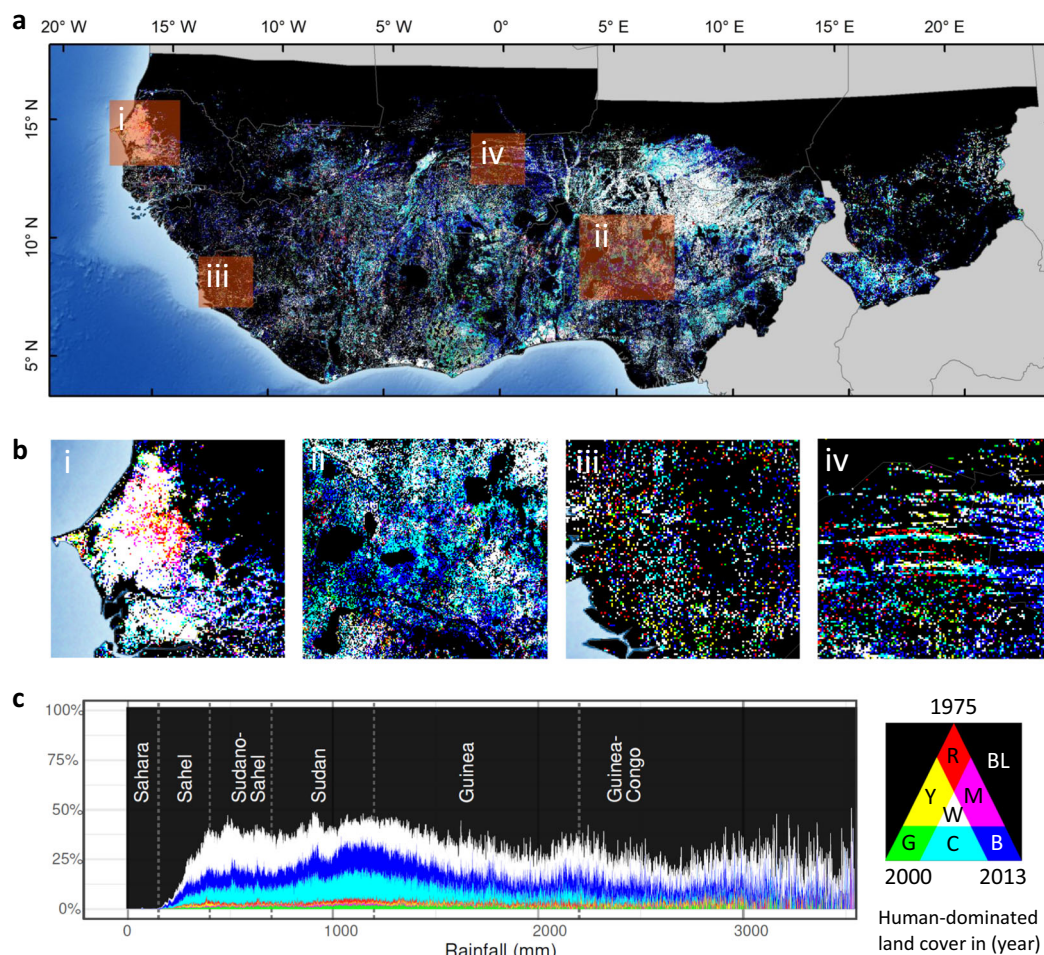


Fig. 4 Spatial patterns of persistence and change in natural and human-dominated land cover. **a** Map of eight possible trajectories of change and persistence, illustrated in an red-green-blue (RGB) composite where each primary color represents a binary layer (human-dominated = 1, natural = 0) at one time period: red is assigned to the 1975 period, green to the 2000 period, and blue to the 2013 period. The resultant trajectories are: black (BL)—persistent natural land cover, white (W)—persistent human-dominated land cover, blue (B)—transition from natural to human-dominated 2000–2013, cyan (C)—transition from natural to human-dominated 1975–2000, red (R)—transition from human-dominated to natural 1975–2000, yellow (Y)—transition from human-dominated to natural 2000–2013, magenta (M)—human-dominated to natural to human-dominated, green (G)—natural to human-dominated to natural. **b** Four subsets highlighting a range of different dynamics in selected locations: (i) old agricultural area with expansion and abandonment, (ii) recent large-scale commercial farming, (iii) shifting cultivation, (iv) agricultural land use modulated by topography. **c** Proportions of persistence and change trajectories along the rainfall gradient show steep increase in human-dominated land cover across the Sahel sub-region, fewest natural land cover from the Sudano-Sahelian through the northern Guinean sub-regions, and a predominance of recent transitions to human-dominated land cover in the recent (2000–2013) compared to the earlier (1975–2000) time interval.

spectral reflectance-based algorithm (such as the distinction between agriculture and savanna) the breadth of land cover categories in the dataset includes some rather similar categories, whose subtle differences arguably make it hard to reliably distinguish them (such as savanna and herbaceous savanna). More interpretation errors are likely to have occurred in the 1975 dataset than in the later ones, when more ancillary data sources were available to help interpretation. Some of the potentially resultant interpretation errors are expected to be minimized by merging the individual land cover categories into two broader categories of natural and human-dominated land cover, as done in the following section.

Spatio-temporal patterns of the human footprint across West Africa. Aggregation of the thematically detailed land cover dataset into natural and human-dominated land cover (Table S1) revealed spatio-temporal patterns of persistence and change of the human appropriation of the land, which reflect the interplay of

environmental conditions, socioeconomic constraints, and opportunities, as well as past and current land use policies (Fig. 4a and b).

Human pressures notwithstanding, almost three quarters (73%) of the study region was persistently covered by natural land cover types. A significantly smaller portion (10%) of the study region was continuously human-dominated at least since 1975. This includes long-standing agricultural areas (the old Peanut Basin of Senegal, the Seno Plains of Mali, the Niger-Nigeria border area) as well as the densely populated urban and peri-urban areas scattered throughout the region, particularly along the Atlantic coast and in Nigeria (Supplementary Fig. 2). Human-dominated land cover more than doubled from 493,000 km² in 1975 to 1,121,000 km² in 2013, raising its share from 10% to 23% of the study region. Over the same time interval, only 1.3% reverted from human-dominated to natural land cover—roughly as much as transitioned back and forth between natural and human-dominated.

Human-driven land conversion favored the Sudanian to northern Guinean sub-regions (Fig. 4c). In these semi-arid to

sub-humid zones, climatic conditions are most suitable for rainfed agriculture, which occupies by far the most land of all human-dominated land cover types (91% in 2013) and constitutes 93% of the transitions from natural to human-dominated land cover types. The spatial patterns of human-dominated land cover and its expansion over time highlight not only favorable climatic conditions but also a preference of the more easily workable sandy soils for farming, which were taken under cultivation first (Supplementary Fig. 3). Especially in the semi-arid zone, the extent of sandy soil corresponds very well to the spatial pattern of agricultural lands¹⁴.

Four specific examples illustrate the interplay of natural and socio-economic forces behind the observed geographic patterns: Senegal's Old Peanut Basin (Fig. 4b i) is an example of an extensive agricultural area under continuous cultivation, the early development of which dates back to the 19th century³⁸. The withdrawal of agricultural subsidies since the mid-1980s, coupled with a decline in soil fertility, led many farmers to abandon their fields in favor of other economic activities³⁹. The abandonment of agriculture and its reversion back to savanna shows as human-dominated to natural transitions in the east of the basin. Simultaneously, agriculture expanded to the southeast, where rainfall is higher and generally more reliable. The spatial pattern of eastward expansion also reflects the preference of agriculture for easily workable sandy soils (see Supplementary Fig. 3). While the area under cultivation has increased less in Senegal than in other countries of the region⁴⁰, our analysis reveals that its spatial pattern has been far from stable.

The Middle Belt of Nigeria (Fig. 4b ii) shows the imprint of a policy environment favorable to large-scale commercial farming⁴¹. Here, the savanna landscape was little cultivated in 1975, but vast stretches of land were taken under the plow by 2013. Nature and wildlife reserves are the only remaining patches of natural land cover. By contrast, small-scale slash and burn shifting cultivation is the conventional agricultural practice in the woody savannas and woodlands of Sierra Leone (Fig. 4b iii)⁴². The cyclical succession of cultivation and fallow with regrowth forms a patchwork of transitions from natural to human-dominated land cover and vice versa.

In northern Burkina Faso, the observed spatial patterns of land cover change can be explained by the underlying topography (Fig. 4b iv). Agricultural development has favored east-west-oriented fossil dunes because of good soil water availability and ease of tillage. While the dunes in Burkina Faso were cultivated early and partly given up during the Sahel droughts of the 1970s and 1980s, to the East thereof, in western Niger, agricultural expansion onto the dunes has been recent⁴³.

The aggregation of the original, thematically rich dataset into natural and human-dominated land cover allowed to visualize the extent and dynamics of the human appropriation of land in West Africa in one single map, while minimizing any noise that might have resulted from mis-interpretation of subtle differences between land cover types in the creation of the dataset. On the other hand, changes within these two broad categories remain hidden in this binary representation. Examples include urban expansion targeting croplands⁴⁴, conversion from forest to degraded forest, loss of steppe or savanna to bare soil or sandy cover⁴⁵.

High land cover change intensities in the vicinity of new settlements. Settlements and their expansion account for a minor part of global land cover and change in terms of area^{4,46}. In West Africa, the land cover category "settlement" made up 0.3% and 0.7% of the total study region in 1975 and 2013, respectively. However, the impact of settlements on land cover change far exceeds their immediate locations^{47,48}.

An analysis of change intensities at a progressing distance from points that transitioned from other land cover categories to settlement shows how land cover transitions are spatially linked rather than isolated and illustrates how the expansion of settlements is associated with other land cover changes in its vicinity (Fig. 5). The average change intensity within a window of 10 km around a new settlement point exceeded the uniform change intensity of the region by up to a factor of three (1.64% yr⁻¹ compared to 0.53% yr⁻¹ uniform change intensity for 1975–2000; 2.72% yr⁻¹ compared to 0.91% yr⁻¹ uniform change intensity for 2000–2013). Change intensities dropped sharply within 20–40 km from the new settlement points and declined further with increasing distance (Fig. 5a).

The predominant types of land cover transitions varied with distance from the new settlement as well as with bioclimatic zone (Fig. 5b). Within a distance of 10 km of a new settlement point, settlement expansion made up a large share of transitions. Transitions from various natural land covers to agriculture were also important in close vicinity of new settlements, illustrating the link between population growth and increasing demands for agricultural products⁴⁹. At increasing distance (40 km) from a new settlement point, in addition to transitions to agriculture, transitions characterized by a degradation of woody cover play a role in the humid Guinean and Guineo-Congolese sub-regions, suggesting an effect from the increased demand for fuel wood and charcoal in the expanding settlements. This observation is in line with findings of fuel wood and charcoal consumption contributing significantly to woody cover loss in the region^{50,51} and lends some spatial detail to those national-scale findings.

In the semi-arid Sahelian to Sudanian zones, the most important land cover transitions at this medium distance (40 km) and beyond were from savanna to agriculture, whereas reverse transitions from agriculture back to savanna also occurred. Within a distance of 300 km, patterns of transitions approached those of the entire region and involve mostly savanna and agriculture, the two largest land cover categories.

Some singularities stood out on the dry margin: Savanna to steppe transitions emerged as a commonly observed land cover trajectory in the Sahel, which can be interpreted as associated with the widely reported loss of tree cover⁵². The majority of the steppe to sandy transitions happened before 2000, when the region was affected by long-lasting, severe droughts. Both of these transitions represent a land cover degradation characterized by a loss of the quantity and quality of the vegetation.

Conclusions

Our findings for West Africa support the notion of an Earth system driven by human activity^{4,48}, with human-dominated land cover categories such as different forms of agriculture and settlements more than doubling their share of the total area (from ~10% to ~23%) at the expense of natural land covers. Population pressure as a key driving force for land cover changes is also evidenced by a threefold increase in land cover change intensity observed in the vicinity of new settlements points. Our change intensity analysis using a thematically detailed dataset showed that, despite the increasing pressure on land resources, intact forest was systematically avoided for transition to agriculture, whereas degraded forest and savanna were targeted most throughout the region.

The finer-scale spatial patterns of the human footprint in West Africa however indicate that simplistic notions of causal relationships between population growth and land cover change are not always sufficient to explain the complexity of land cover outcomes. These patterns were shaped not only by population pressure and the physical environment, but also by changing

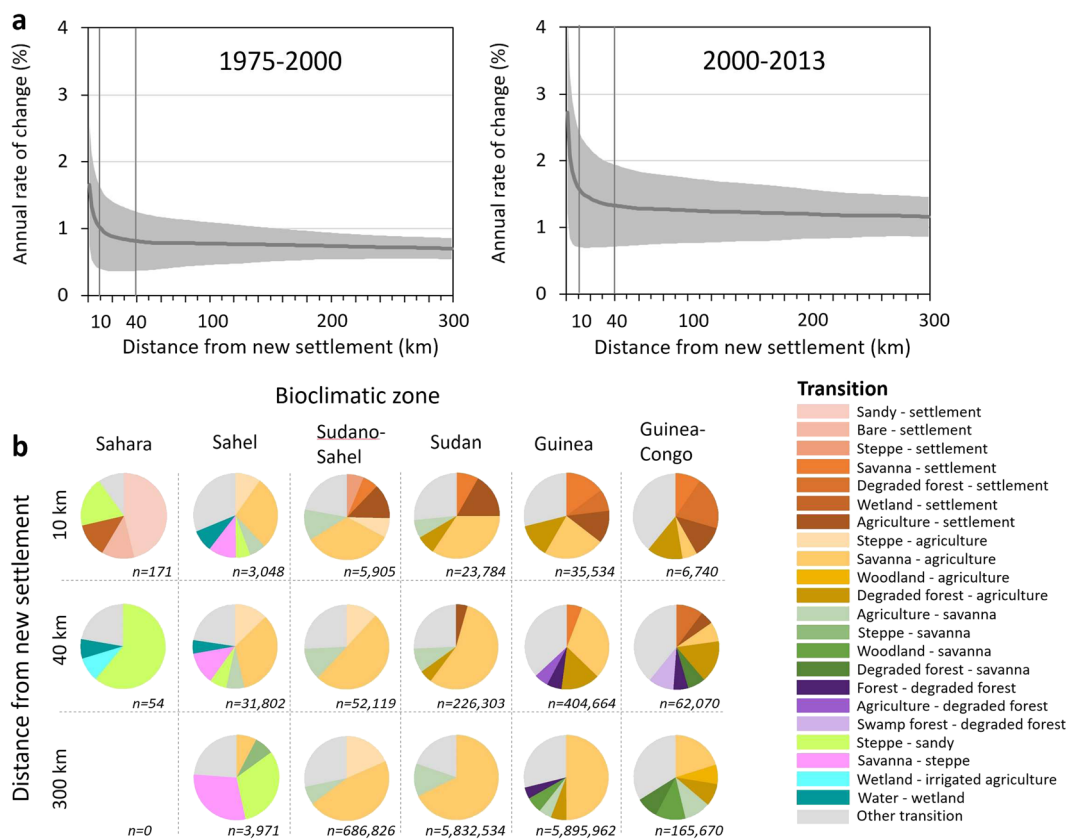


Fig. 5 Land cover change associated with population pressure. **a** Land cover change intensities (averages and standard deviations) decrease progressively with distance from points newly transitioned to settlement. The 2000–2013 interval reflects higher overall change intensities than the 1975–2000 interval. **b** Types of land cover transitions found within windows of 10, 40, and 300 km distance from new settlement points for the 2000–2013 interval by sub-region. “Other transition” encompasses the sum of individual transition types that each make up <5% of the respective windows. “n” denotes the number of pixels taken into account.

socioeconomic conditions and policies, which favor certain pathways of change and prevent others.

With West Africa’s population projected to continue its unabated increase over the next decades⁵³, a further intensification of land cover change can be expected. Taking the past as an indicator of the future, the observed patterns of change and persistence give an idea of what types of future changes might occur, and where: In the absence of strong efforts towards intensification of agriculture, continued expansion of cultivation into land of progressively lower production potential is to be expected, especially in the Sudano-Sahelian to Guinean bioclimatic zones. While rainfed agriculture has been the dominant expanding class in terms of area, the intensely gaining but smaller categories ‘settlements’, ‘plantations’, and ‘irrigated agriculture’ are likewise expected to continue to replace natural land cover and threaten biodiversity at a rapid rate, and in the case of irrigated agriculture impact salinization, river flows, and groundwater as well⁵⁴.

Initiatives and policies that encourage agricultural intensification are needed to counteract the tendencies of agriculture to spatially expand and further encroach into savanna, woodlands, and forests. As crop yield gaps are typically large in West Africa, the potential for yield improvements through fertilizer use, improved crop varieties and integrated soil fertility management is considerable⁵⁵. Defining and protecting wildlife corridors connecting parks and reserves where larger stretches of savanna and forest are still intact may prevent the complete fragmentation of remnant primary vegetation observed for example in Nigeria’s Middle Belt.

Beyond informing policy recommendations, an improved understanding of land cover trajectories is important for a

realistic estimation of the impacts of changed land cover on surface fluxes at local and regional scales⁵, potentially amplifying aridity increases under global warming⁵⁶ as well as temperature and humidity extremes⁵⁷. Despite its important role in the surface energy budget, agricultural expansion has so far been inadequately represented in regional climate model projections^{58,59}. Finally, land cover change plays a part in the global carbon balance, with carbon densities of vegetation and soil differing between land cover categories such as forest, degraded forest, savanna, steppe, and croplands⁷. Detailed and accurate knowledge of the extent and type of land cover changes will afford more precise estimates of carbon added to or removed from the atmosphere. In view of the large area gains of cropland in semi-arid West Africa, promoting agroforestry as an effective climate change adaptation and efficient carbon sink⁶⁰ could counter the negative impacts of large-scale savanna–cropland transitions on the carbon balance.

Methods

Study region and bioclimatic sub-regions. The study region was defined by the extent of the multi-temporal land cover dataset used and comprises 16 West African countries and Chad with a total population of almost 400 million in 2018⁵³. Of the four Saharan countries Mauritania, Mali, Niger, and Chad, only the southern portions were included (Fig. 1c). The study region extends across 14 degrees latitude and 40 degrees longitude and corresponds to an area of almost five million square kilometers. It spans a north–south precipitation gradient from close to zero to over 3000 mm mean annual precipitation, which is steepest in the Sudano–Sahelian transition zone and defines vegetation and land cover, modulated by soils, geology, and topography.

We used rainfall isohyets derived from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS)⁶¹ mean annual rainfall (1981–2013) to divide the study area into the Saharan (<150 mm), Sahelian (150–400 mm),

Sudano-Saharan (400–700 mm), Sudanian (700–1200 mm), Guinean (1200–2200 mm), and Guineo-Congolese (>2200 mm) sub-regions.

Land cover data. Our analysis takes advantage of a thematically detailed and temporally consistent land cover dataset of West Africa provided by the United States Geological Survey (USGS)²³. This dataset was created from expert image interpretation of primarily Landsat, complemented with aerial photographs, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and finer resolution satellite imagery as well as field observations, using a sample-based approach²². It comprises over 1.2 million interpretation points on a regular 2 km-spaced grid, for which land cover was interpreted and assigned to one of 23 thematic classes at three time periods (circa 1975, circa 2000, and circa 2013) (see Supplementary Table 1 and Supplementary Fig. 1). The visual interpretation approach overcomes some of the known shortcomings inherent to available fully automated algorithm-generated land cover classifications in West Africa, such as the poor spectral separability of cropland and savanna and the effects of inter-annual variability⁶², as the analyst familiar with the territory is able to take spatial context into account. Acquisition dates of the 244 Landsat scenes covering the study region varied depending on cloud cover, but are skewed to the dry season. The method enables to incorporate multiple images from different sources and of different resolutions, as needed to support the interpretation. With the same locations sampled through time, interpreted using spatial-temporal map logic and harmonized by several image interpreters, the dataset is considered consistent between time periods and therefore offers a unique basis for characterizing and analyzing change in land cover²².

Population data. Population estimates by country were obtained from the United Nations Department of Economic and Social Affairs (UN ESA)⁵³ at yearly intervals from 1950 to 2013 and projections to 2100. They were aggregated to the study region and annual growth rates were calculated (Fig. 1a). For a spatial representation of population patterns (Supplementary Fig. 2), Gridded Population of the World (GPW v4) population density data for 2000 were obtained from the Center for International Earth Science Information Network^{63,64}. Since pre-2000 and post-2000 GPW population density data are not compatible with one another because of the use of different administrative levels in the gridding process, we use data from the year 2000 only to represent the differences in population pressure in the different zones of the study region (Fig. 2). Although gridded population data from the WorldPop Project⁶⁵ would have been of finer resolution than the GPW v4, the fact that they result from a multi-variable modeling approach, which includes land cover as a predictor variable, made them unsuitable for our purposes of relating land cover to population densities.

Systematic analysis of land cover change. Transition matrices of changes in land cover between 1975, 2000, and 2013 (Supplementary Data 1) were generated from the land cover data. We systematically analyzed these transition matrices adapting the intensity analysis framework, which hierarchically uncovers patterns of change from the broader to the more detailed levels^{24,25}.

In the first level of analysis, we computed land cover change intensities, expressed as annual rates of change, by time interval and sub-region. This adds a spatial dimension to the interval level of analysis presented in Aldwaik and Pontius (2012)²⁴. We compared the rates of change against a uniform rate of change as reference, which is a hypothetical rate of change if the total observed change were uniformly distributed between time intervals and among sub-regions. The comparison reveals which time interval and sub-regions have experienced relatively slow versus relatively fast change.

In the second level of analysis, corresponding to the “category level” in Aldwaik and Pontius (2012)²⁴, we extracted (1) the magnitude of change for each land cover category as gross gains and gross losses in km² and (2) annual rates of change (% yr⁻¹) for both gains and losses for each land cover category, as well as the uniform change intensity over the same time interval. This allows to distinguish actively changing (i.e., exceeding the uniform change intensity) from dormant (i.e., changing at a rate below the uniform change intensity) land cover categories. Finally, a third level of analysis (“transition level”) allowed us to probe the transition matrices for systematic transitions to any particular category to determine which other categories this category systematically targeted or avoided for transition. We examined transitions to agriculture, the most area-gaining land cover category, to unveil which other land cover categories were systematically replaced by expanding agriculture.

The intensity analysis thus adds a way of determining the significance of change that is independent of the magnitude of change, which is heavily influenced by the size of the categories at the beginning time period thereby concealing information about the intensity of change.

Analysis of spatial patterns of natural and human-dominated land cover. We aggregated the 23 thematic land cover categories into binary layers of two categories, natural and human-dominated land cover, at each of the three time periods (1975, 2000, 2013) to be able to simultaneously visualize spatial and temporal patterns of human appropriation of the land. The human-dominated land cover

category includes different forms of agriculture, settlements, and open mines; the remaining 16 land cover categories were aggregated into natural land cover and comprise different vegetated and unvegetated land covers as well as water (Fig. 1b). The natural land cover categories are not excluded from human use, but they were not deliberately planted or otherwise developed. Eight possible trajectories are represented by the combination of three binary layers of natural/human-dominated land cover (Fig. 4): persistent natural and human-dominated land cover; early and late gains of human-dominated land cover; early and late losses of human-dominated land cover; back and forth transitions starting with human-dominated and natural land cover, respectively.

Neighborhood analysis. Rates of change were computed in rectangular windows around all points at which land cover transitioned from any other category to settlement. These “new settlement points” were used as a proxy for increased population pressure. Rates of change were averaged over all windows. Window sizes were progressively expanded from one grid cell (2 × 2 km) to 150 grid cells (300 × 300 km). Individual from-to land cover transitions were counted within windows of 10, 40, and 300 km distance from new settlement points in each of the six bioclimatic sub-regions to characterize the dominant transition types associated with increased population pressure. Transitions that made up <5% of the respective window were summed up into “other transitions”. Only windows completely falling within the region of interest were included. The number of pixels (*n*) taken into account per bioclimatic zone increases with the incidence of settlement expansion and with window size (distance from new settlement), but it decreases in the Saharan and Sahelian zones as windows become so large that they are not fully contained within one bioclimatic zone anymore and therefore excluded from the analysis.

Data availability

All data used in this study are freely and publicly available. Land cover data are available from USGS (<https://eros.usgs.gov/westafrica/data-downloads>). Population time series can be obtained from the UN Department of Economic and Social Affairs (<https://population.un.org/wpp/>). Gridded population data are available from the Gridded Population of the World (GPWv4) project (<https://sedac.ciesin.columbia.edu/data/collection/gpw-v4>). The Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) rainfall estimates can be obtained from the Climate Hazard Group (<https://chg.geog.ucsb.edu/data/chirps/>). The soil property data are available from the International Soil Reference and Information Centre (ISRIC) (<https://www.isric.org/projects/soil-property-maps-africa-250-m-resolution>).

Code availability

All analyses were implemented in the scientific programming language Interactive Data Language (IDL) version 8.6. The specific code can be obtained upon request from the corresponding author.

Received: 6 May 2020; Accepted: 2 November 2020;

Published online: 27 November 2020

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Acknowledgements

We acknowledge funding from the U.S. Geological Survey (USGS), Desert Southwest Cooperative Ecosystem Studies Unit agreement #G15AC00447 (S.M.H.) and the Danish Council for Independent Research (DFR) grant Sapere Aude (9064-00049B) (M.B.)

Author contributions

S.M.H. designed the study and conducted the analyses with support by M.B. and R.F. S. M.H., R.F., M.B., and K.R. collaboratively interpreted the results. S.M.H. drafted the manuscript with contributions by all authors.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is available for this paper at <https://doi.org/10.1038/s43247-020-00053-y>.

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Peer review information Primary handling editor: Heike Langenberg.

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